An Overview of the Bluetooth Wireless Technology

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ABSTRACT

The Bluetooth™[1] wireless technology is designed as a short-range connectivity solution for personal, portable, and handheld electronic devices. Since May 1998 the Bluetooth SIG has steered the development of the technology through the development of an open industry specification, including both protocols and application scenarios, and a qualification program designed to assure end-user value for Bluetooth products. This article highlights the Bluetooth wireless technology.[2]

INTRODUCTION

For the last few years the wireless world has been bombarded daily with information about a new generation of radio frequency (RF) technologies that would profoundly impact, if not revolutionize, the way we live and contact our businesses. This new generation of technologies spans the full spectrum of wireless communications coverage. Third generation (3G) wireless technologies are being developed to enable personal, high-speed interactive connectivity to wide area networks (WANs). The IEEE 802.11b wireless local area network (LAN) technology finds itself with an increasing presence in corporate and academic office spaces, buildings, and campuses. Furthermore, with slow but steady growth, the 802.11b technology is making inroads into public areas such as airports and coffee bars.

WAN and LAN technologies enable device connectivity to infrastructure-based services, either through a wireless carrier provider or through a campus or corporate backbone intranet. The other end of the coverage spectrum is occupied by the short-range personal wireless connectivity technologies that allow personal devices to communicate with each other directly without the need for an established infrastructure. At this end of the coverage spectrum the Bluetooth wireless technology offers to the personal connectivity space the benefits of omni-directionality and the elimination of the line of sight requirement of RF-based connectivity. The personal connectivity space resembles a communications bubble that follows people around and empowers them to connect their personal devices with other devices that enter the bubble. Connectivity in this bubble is spontaneous and ephemeral and can involve several devices of diverse computing capabilities, unlike wireless LAN solutions that are designed for communication between devices of sufficient computing power and battery capabilities.

The Bluetooth wireless technology[3] will serve primarily as a replacement of the interconnect cables between a variety of personal devices, including notebook computers, cellular phones, personal digital assistants (PDAs), digital cameras, etc. The Bluetooth wireless technology aims to serve as the universal low cost, user friendly, air interface that will replace the plethora of proprietary cables that people need to carry and use to connect their personal devices. While personal devices typically communicate based on the RS-232 serial port protocol, proprietary connectors and pin arrangements make it impossible to use the same set of cables to interconnect devices from different manufactures, and sometimes even from the same manufacturer. The primary focus of the Bluetooth wireless technology is to provide a flexible cable connector with reconfigurable pin arrangements permitting several personal devices to interconnect with each other.

Another focus of the technology is to enable a uniform interface for accessing data services. A user using any number of data-capable devices will be able to connect to a LAN access point that provides access to, for example, the corporate intranet infrastructure and services. Likewise, the user will be able to connect to her cellular phone and access WAN data services. Applications can then be written that could provide the user with a similar connectivity experience connecting to data service in either manner. Connecting to data services through one's cellular phone gives rise to the concept of a *personal gateway*. People will carry their personal gateways wherever they go. The personal gateway will serve as a facilitator in accessing remote data services, with the added convenience that it can be kept hidden away from the line-of-sight of its communicating Bluetooth partner. The Bluetooth wireless technology enables the unobtrusive separation of the functionality of connecting to a data service from viewing and interacting with the information provided by the

[1] Bluetooth is a trademark owned by the Bluetooth SIG, Inc., USA.

[2] Any opinions expressed in this article represent only the personal opinions of the author and do not reflect a position of the author's employer or anybody else's.

[3] According to the Bluetooth brand requirements document, the term "Bluetooth" must always be used as an adjective. Furthermore, when the term "Bluetooth" is used to denote the corresponding technology, the term "wireless" must be inserted between Bluetooth and technology. The author recognizes that the above rules are not always followed and the term "Bluetooth" has grown to represent both the technology and the whole industry behind it.

data service. Thus a PDA can be used as a more convenient I/O device for entering and receiving data, while using the personal gateway purely for communicating with the wireless data carrier.

Yet another focus item for the Bluetooth wireless technology is to enable ad hoc connectivity among personal devices. This will permit individuals to form collaborative groups, for example, during a conference meeting, to exchange data without the need to rely on an infrastructure to support their communication.

In this article, we present an overview of the Bluetooth wireless technology. This article is organized as follows. We present a history of the Bluetooth wireless technology, followed by a discussion of the Bluetooth specification, including the core and the profile portions of the specification. We conclude with a summary of the article.

THE HISTORY OF THE BLUETOOTH WIRELESS TECHNOLOGY

The development of the Bluetooth industry standard started late in the winter of 1998 when Ericsson, IBM, Intel, Nokia, and Toshiba formed the Bluetooth Special Industry Group (SIG) to develop and promote a global solution for short-range wireless communication operating in the unlicensed 2.4 GHz ISM (industrial, scientific, medical) band.

The name Bluetooth comes from the Danish king *Harald Blåtand* (Bluetooth). King Bluetooth is credited with uniting the Scandinavian people during the 10th century. Similarly, the Bluetooth wireless technology aims to unite personal computing devices. The name was chosen temporarily to describe the yet unannounced development project. However, the search for a new name never came to a successful fruition and the temporary name became permanent. In retrospect, the selection of this joyful name can be credited highly for the recognition and acceptance the technology has received so far.

To facilitate the wide acceptance of this new technology, the SIG decided to offer all the intellectual property explicitly included in the Bluetooth specification royalty-free to adopter members of the technology when it is used to introduce Bluetooth products in the market. The SIG announced its existence and intentions to the public in May 1998, joined at the time by approximately 70 adopter members. As of this writing there are approximately 3000 adopter members. A little over a year later, in the summer of 1999, the over 1600-page Bluetooth specification version 1.0A became publicly available. Due to the Bluetooth SIG license agreement, the development of the specification is not made available to the general public until it is finished and approved by the Bluetooth SIG. Adopter members have the privilege to look at the specification prior to its public availability.

The Bluetooth specification, currently at version 1.1, comprised the following two parts, which we discuss later in the article:

- The core specification defining the radio characteristics and the communication protocols for exchanging data between devices over Bluetooth radio links.
- The profile specification that defines how the Bluetooth protocols are to be used to realize a number of selected applications.

To make free use of the intellectual property in the Bluetooth specification, adopter members need to qualify any Bluetooth products they intent to bring to market through the Bluetooth qualification program (BQP). The BQP includes radio and protocol conformance testing and profile conformance testing (when applicable) as well as interoperability testing.

In December 1999 the promoter group increased from five to nine with the addition of 3Com, Lucent, Microsoft, and Motorola. As of early 2001, Agere, a Lucent spinoff comprising its former microelectronics division, has taken the place of Lucent in the promoters group.

In March 1999 the IEEE 802.15 standards working group was created to develop a family of communications standards for wireless personal area networks (WPANs).[4] In the first meeting of the new working group in July 1999, the Bluetooth SIG submitted the just created Bluetooth specification as a candidate for an IEEE 802.15 standard. The Bluetooth proposal was chosen to serve as the baseline of the 802.15.1 standard. As of this writing, the development of the draft standard is in its final stages, having successfully completed two sponsor ballots. In addition to the IEEE 802.15.1 activity, the IEEE 802.15.2 task group studies coexistence issues between 802 wireless technologies. The 802.15.3 task group is developing standards for high-rate radios (>20 Mb/s). Finally, the 802.15.4 task group is developing standards for low-rate radios (<200 kb/s).

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THE BLUETOOTH SPECIFICATION

The Bluetooth specification has been written primarily as an implementation manual rather than a formal communications standard document. This aspect of the specification reflects its development process by a group of engineers that actually developed the technology in parallel with the development of the specification. These engineers wrote in a prose style, describing in the specification their experiences gained in implementations. This is in contrast to the formal language commonly used in a formally developed standard. This approach has its pros and cons. On the upside, the specification is easier to read than a formal standards document. On the downside, using prose, which is naturally imprecise, the specification is sometimes open to conflicting interpretation. The latter issue is being addressed through an errata resolution process.

Figure 1 depicts the Bluetooth protocol stack, which also shows the application and profiles "layer" for completeness. (We discuss the latter later in this section.) The protocols in the stack have been grouped in two categories: the *transport* and the *middleware* protocols. The transport protocols comprise protocols developed exclusively for the Bluetooth wireless technology. These protocols are involved in all data communications between two Bluetooth devices. The middleware protocols comprise both Bluetooth-specific protocols and other adopted protocols. These protocols are used selectively to enable

[4] *WPAN is a trademark of IEEE.*

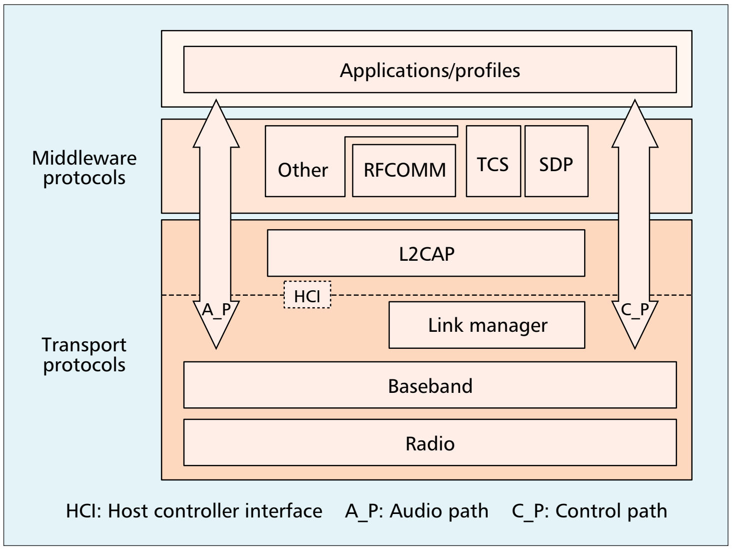

Figure 1. *The Bluetooth protocol stack.*

different applications, including both legacy and new applications, to exchange data using the Bluetooth wireless technology. Whenever desired, the middleware protocols shield these applications from the specifics of the Bluetooth transport protocols.

This grouping of the protocols in the Bluetooth protocol stack is not part of the specification. Rather, it is used here as a natural grouping of the protocols for ease of presentation.

THE TRANSPORT PROTOCOLS

The Radio — The radio layer defines the technical characteristics of the Bluetooth radios. A Bluetooth radio operates on the license-free 2.4 GHz ISM band and is compliant with FCC part 15 regulations for intentional radiators in this band. It employs a fast (1,600 hops/sec), frequency-hopping, spread-spectrum (FHSS) technique. The radio hops in a pseudo-random fashion on 79 one-MHz channels.[5] The frequencies are located at $(2{,}402 + k)$ MHz, $k = 0, 1, \ldots, 78$.

The modulation technique is a binary Gaussian frequency shift-keying (GFSK) and the baud rate is 1 Msymbol/s. Hence, the bit time is 1 ms and the raw transmission speed is 1 Mb/s. The Bluetooth radios come in three power classes, depending on their transmit power. Class 1 radios have transmit power of 20 dBm (100 mW); class 2 radios have transmit power of 4 dBm (2.5 mW); class 3 radios have transmit power of only 0 dBm (1 mW). Due to the power and cost constraints of the various personal devices that use Bluetooth radios, class 3 and class 2 radios are expected to be the ones mostly used in these devices.

The Baseband — The baseband defines the key procedures that enable devices to communicate with each other using the Bluetooth wireless technology. The baseband defines the Bluetooth piconets and how they are created, and the Bluetooth links. It also defines how the transmit resources are to be shared among several devices in a piconent, as well as the low-level packet types.

The Bluetooth Address and Clock — Each Bluetooth device has two parameters that are involved in practically all aspects of Bluetooth communications. The first one is a unique IEEE-type 48-bit address assigned to each Bluetooth radio at manufacture time. The *Bluetooth device address (BD_ADDR)* is engraved on the Bluetooth hardware and it cannot be modified. The second parameter is a free-running 28-bit clock that ticks once every 312.5 µs, which corresponds to half the residence time in a frequency when the radio hops at the nominal rate of 1,600 hops/sec.

Bluetooth devices can communicate with each other by acquiring each other's Bluetooth addresses and clocks, as will be further described later.

The Bluetooth Piconet — A piconet is a collection of Bluetooth devices that can communicate with each other. A piconet is formed in an ad hoc manner without any infrastructure assistance, and it lasts for as long as the creator of it needs and is available to communicate with other devices. A piconet contains at least one device identified as the *master* of the piconet and at most seven other devices identified as *slaves* with which the master is *actively* involved in communications. The terms master and slave are relative to a particular existing piconet. The terms are not assigned to the radio units at manufacture time. A Bluetooth radio may serve either as a master or slave at different times.

To identify each slave, the master of a piconet assigns a locally unique *active member address (AM_ADDR)* to the slaves participating in active communications in the piconet. The master regulates and controls who transmits and when. While up to seven slaves may be actively communicating in a piconet at one time, additional devices may be registered with the master and be invited to become active whenever necessary. These additional devices are called *parked*. Bluetooth devices not associated with any piconet are in *stand-by* mode. Figure 2 shows two piconets with a number of slaves and parked devices associated with them, and a few standby devices. Bluetooth piconets can coexist in time and space independently of each other. Furthermore, a single device may be a member of several piconets, a case referred to as *scatternet* in Bluetooth parlance.

The communications channel in a piconet is defined as the sequence of the frequency hops followed by the piconet members in a synchronized manner. The transmit and receive time axis are slotted, with each slot lasting the duration of a nominal frequency hop, 625 µs. Each baseband transmission resides fully within the boundaries of a slot. However, multi-slot packets occupying three or five slots instead are also allowed. During the transmission of a multi-slot packet, the transmit frequency does not change. When frequency hopping resumes, it resumes with the frequency whose turn it would have been if the devices were to use only single-slot transmissions.

To maintain time synchronization for the hops, slaves utilize the Bluetooth clock of the master and the fact that hops occur in multiples of 625 µs; slaves actually maintain the offset time between their Bluetooth clock and that of

[5] *The specification permits a reduced channel hop over only 23 channels for countries that have restrictions in their corresponding ISM band.*

their master. Slots in a piconet are identified as even or odd according to the value of the second least significant bit of the Bluetooth clock of the master; recall that the Bluetooth clock ticks at a rate twice that of the slot rate. To recreate the frequency hop sequence in a piconet, a slave utilizes the Bluetooth address of the master of the piconet. Furthermore, the Bluetooth clock of the master identifies the particular frequency to be used at a particular slot. Therefore, the communications channel in a piconet is fully identified by the master. As a result, in the case of scatternets a device can serve as a master for only one piconet, otherwise the two piconets cannot be distinguished from each other.

The master and the slaves alternate transmit opportunities in a *time-division duplex* (TDD) fashion. In particular, the master transmits on even numbered slots, as defined by the master's Bluetooth clock, while the slaves transmit on odd numbered slots (recall that each slot lasts 625 μs). A slave can transmit only if the master has just transmitted to this slave. A transmission may last one, three, or five slots; however, the specification requires that only the one-slot transmissions be mandatory. In the case of scatternets, a device cannot receive or transmit data simultaneously in two or more piconets. However, such a device may time-share its participation in each piconet over non-overlapping time intervals.

To engage in communications in a piconet, the slaves in the piconet need to know the *BD_ADDR* and Bluetooth clock of the master. Likewise the master needs to know the identities of the slaves. This information is acquired in two phases: the inquiry phase, for locating devices, and the the paging phase, for inviting specific devices to join a piconet. A good overview of these phases is given in J. Haartsen's "The Bluetooth Radio System" in [1].

The *inquiry* process is a device discovery process during which the master of a future piconet discovers other devices in its vicinity. The master makes its presence known by transmitting inquiry messages. Devices that perform inquiry scan, that is, search actively for inquiry messages, respond with inquiry response messages that, among other things, contain the *BD_ADDR* of the device.

Armed with the knowledge of the identity of devices in its vicinity, the master of a piconet may explicitly *page* devices to join its piconet. A master with prior knowledge of the identity of a device may skip the inquiry process and go directly to paging the device. If the device does not respond, it may mean that it is not in the transmit range of the paging device.

With the information sent by the paging device to the paged device, the paged device can now join as a slave the piconet whose master is the paging device. After joining the piconet, the master and the slave may negotiate reversal of roles, in which case the (original) master becomes a slave in the piconet whose master will be the (original) slave.

Next we present how masters and slaves exchange data.

The Bluetooth Links and Baseband Packets — There are two types of links supported in the Bluetooth piconet. Between a master and a slave

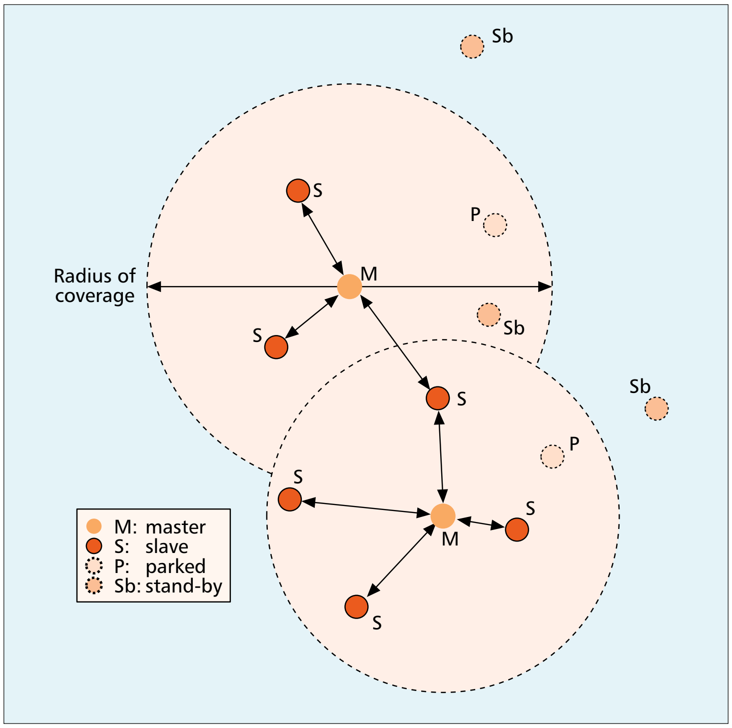

Figure 2. *Bluetooth piconets.*

there is a single *asynchronous connectionless* (ACL) link supported. Optionally, a piconet may support *synchronous connection-oriented* (SCO) links. Up to three SCO links may be supported in a piconet.

The ACL link is a best-effort link appropriate for asynchronous data transmissions. It maintains integrity by using retransmissions and sequence members, as well as forward error correction (FEC) if necessary. The SCO link supports periodic audio transmissions at 64 Kb/s in each direction. SCO traffic is not retransmitted, but it can use FEC mechanisms to recover from transmission errors when they occur.

Figure 3 shows the various baseband packet types. They all contain an *access code* (AC) field, which is used to distinguish transmissions in different piconets. With the exception of the ID packet, all other packets also have a header portion. With the further exception of the poll and null packets, all other packets also have a payload section.

The ID packet is used during inquiry searches and to obtain time synchronization during pages. The poll packet is used by the master to explicitly poll a slave when no payload information needs to be sent to the slave. The *null* packet is used to acknowledge a transmission when no payload information needs to be sent.

The *frequency-hopping sequence* (FHS) packet is used during the creation of a piconet and it is used to pass address (*BD_ADDR* and *AM_ADDR*) and clock information between future masters and slaves. The payload of an FHS packet is encoded with a shortened Hamming code with rate 2/3. The number of bits shown in the figure is after the application of the FEC.

The ACL or SCO packets carry asynchronous

The link manager protocol is a transactional protocol between two link management entities in communicating Bluetooth devices whose responsibility is to set-up the properties of the Bluetooth link.

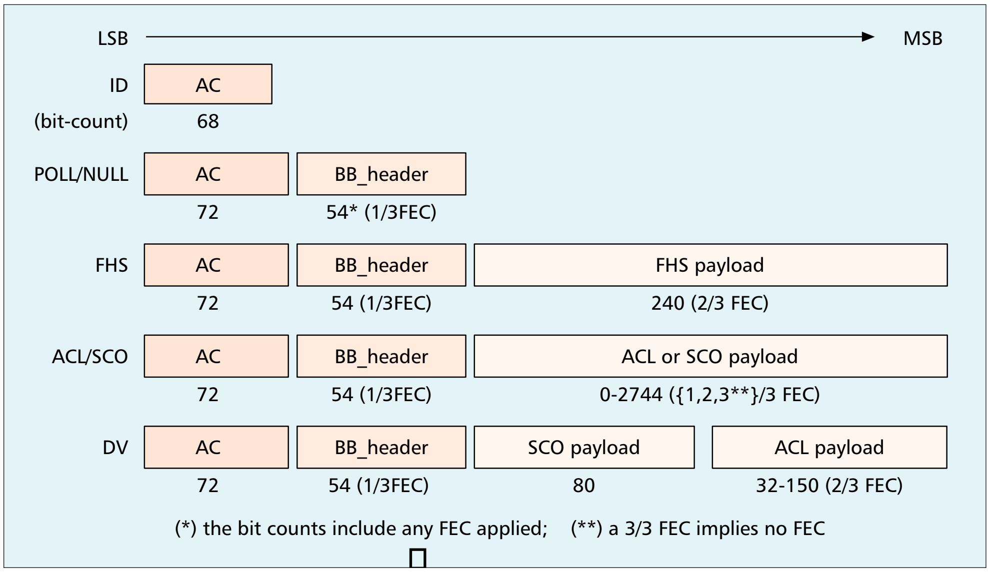

Figure 3. *The baseband packet types.*

and synchronous data in their payload, respectively. The payload of ACL packets may be encoded with an FEC with rate 2/3, or not encoded at all. The payload of SCO packets may be encoded with an FEC with rate 2/3 or 1/3, or not encoded at all. When the FEC with rate 1/3 is used, each bit is simply repeated three times. The *data voice* (DV) packet is a packet that contains both ACL and SCO data and is transmitted at the periodic instances of a regular SCO packet, whenever there is a need to send ACL data to the recipient device of the SCO transmission.

Figure 4 depicts the fields in the header and the payload of a baseband packet. The *AM_ADDR* field identifies the destination slave of a master transmission or the source slave of a slave transmission. The *PDU_type* field identifies the type of baseband packet as shown in Fig. 3. The flags are used for controlling the transmission and retransmission of ACL packets. In particular, ACL packets use a stop-and-go ARQ scheme and a 1-bit sequence number. Furthermore, the ACL link is flow-controlled. The header is protected by an 8-bit header error check (HEC) code. The ACL payload has its own header and body portion (see also Fig. 5) and it is protected with a 16-bit cyclic redundancy check (CRC).

When *AM_ADDR* = b'000', then the packet is a broadcast packet from the master to all the slaves. Broadcast packets are not acknowledged and are not retransmitted.

The *L_CH* field in Fig. 5 is used to identify the logical channel for this baseband transmission. When *L_CH* = b'11', then the body of the ACL packet payload is passed to the link manager and is used for the configuration of the Bluetooth link. When *L_CH* = b'01' or b'01', then the body is passed to L2CAP for further processing (discussed later).

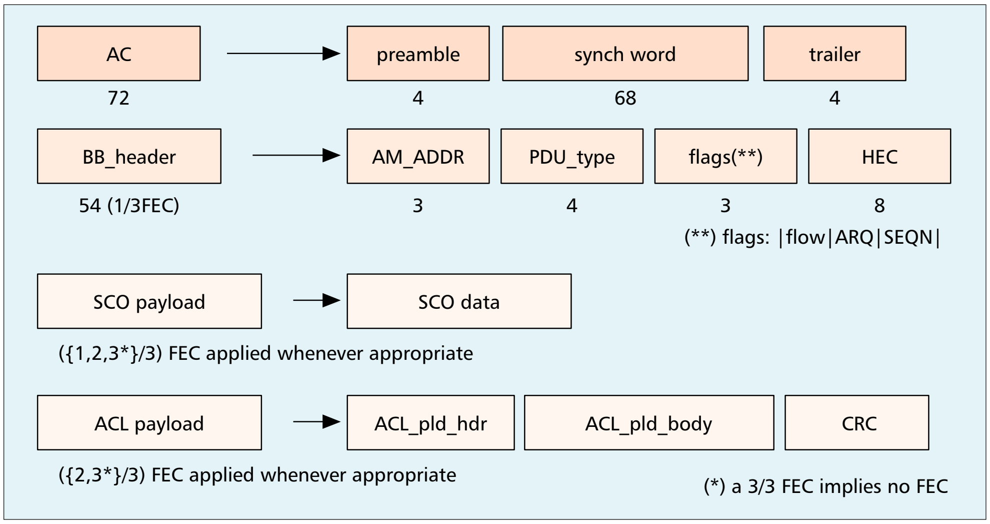

Figure 4. *The baseband packet fields.*

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